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16. ABSTRACT

The importance of corrosion as a product life limiting factor will increase with the necessity to conserve limited resources. Thus, an economic model to assess pollution related corrosion costs becomes a useful decision tool. Physical damage, geographic distribution, maintenance, replacement, substitution, and value lost due to decreased utility or appearances are incorporated into this model. These interrelated factors are subject to individual decisions, which can be assumed in calculating best, worst, and most likely cases for different pollution levels.

17. KEY WORDS AND DOCUMENT ANALYSIS

| a. DESCRIPTORS | b. IDENTIFIERS/OPEN ENDED TERMS | c. COSATI Field/Group |
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| Steels | | 11F |
| Protective coatings | | 11C |
| *Corrosion | | 11M |
| *Economic analysis | | 05C |
| *Mathematical models | | 12A |

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# 1

# ECONOMIC ASSESSMENT OF POLLUTION-RELATED CORROSION DAMAGE

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Many studies have shown that air pollution, especially sulfur dioxide, accelerates the corrosion of steel and zinc (1–9). This effect places an economic burden on the nation by (1) reducing the useful life of products, thus requiring early replacement, (2) increasing maintenance frequency, (3) forcing the use of more costly substitutes, and (4) decreasing the utility of products. A more subtle delayed economic effect is caused by the more rapid consumption of limited resources.

Some of these costs are absorbed by the organization causing the pollution and then uniformly passed to the public in the price of its products. Others are passed nonuniformly to the public through the distribution of pollutants. An example of each will be used to develop a model for assessing the cost to the public of pollution-related corrosion damage.

An example of internalized cost is extra maintenance or early replacement of galvanized steel transmission-line towers belonging to electric utilities with coal-fired power plants. An example of externalized cost includes replacement, maintenance, substitution, and utility loss affecting metal roofing, siding, and guttering.

## TRANSMISSION LINE TOWERS

In 1970, Fink, Buttner, and Boyd [10] estimated there were 194,000 galvanized structural steel transmission line towers in existence. The inventory value was estimated at $1,165 million. The growth rate of electric generating capacity was estimated at 7–8%/yr based on 1950–1970 data. Thus, approximately 95% of generating capacity and, by analogy, 95% of the towers are less than 40 years old.

In recent years there has been a trend to site power plants in rural rather than urban areas. In many cases the plant becomes the major if not the only source of pollution within an area. With transmission lines radiating away from power plants, towers within the area become receptors of pollution. The power company internalizes the cost of its own pollution in the form of extra maintenance or early replacement of towers.

It is important to realize that, although the damage is cumulative and can be annualized, the actual cost of maintenance and replacement is a step function that is dependent on the age and exposure of each tower. The effect of age and location is demonstrated by comparing maintenance costs reported to the Federal Energy Regulatory Commission [11]. Commonwealth Edison's Fisk Plant in Chicago was constructed in 1903 and in 1974 had costs of maintenance to structures of 0.33 mills/kWh. Comparable costs for their Kinkaid, Illinois, plant, constructed in 1967, were 0.08 mills/kWh.

With only about 5% of all towers more than 40 years old and most towers exposed to relatively low levels of pollution, total actual replacement and maintenance costs have been rather small. Only now are utilities becoming concerned about maintenance or possible replacement of galvanized steel transmission line towers and have yet to pay for most of the corrosion damage that has already accumulated. When we will have to pay and how much are questions to be answered by this study.

The Tennessee Valley Authority (TVA) did a study of the thickness of galvanizing on towers in 1964 [12]. They reported 25,000 towers in service varying in age up to 40 years. In an effort to estimate the condition of those towers, they used magnetic, coating-thickness gauges to measure the galvanizing thickness on six different members from the upper halves of the 537 towers. Most of the members were cross members rather than legs. Regression of coating thickness as a function of age based on 3240 values gives:

$$T = (117.0 \pm 0.2) - (0.99 \pm 0.01)\, t \pm 5.2 \quad (1)$$

where $T$ = galvanizing thickness, ($\mu$m)
$t$ = years of exposure
$\pm$ = values are standard deviations

The value 117 $\mu$m represents the estimated mean initial galvanizing thickness and 0.99 $\mu$m/year represents an average corrosion rate on towers exposed to all types of environments (but with 69% in rural areas). Based on these results, an average tower exposed to these average conditions would show discoloration ($T$ = 38 $\mu$m) after 46 years, 5% rust after 84 years, and 95% rust after 165 years.

In 1979, the TVA, through an Interagency Agreement with the Environmental Protection Agency (EPA), did a study of the corrosion of galvanized transmission towers near the Colbert Steam Plant on the Tennessee River [13].

The galvanizing thickness was measured on 19 towers at varying distances and directions from the plant. The location, elevation, year of installation, and other relevant data are given in Table 1.1. The thicknesses were measured with an

TABLE 1.1 DATA RELEVANT TO EXPOSURE OF TRANSMISSION TOWERS

| Tower number | Structure number | Distance and direction from plant (km) | (°C) | Ground elevation (m) | Year installed | Estimated[a] average $SO_2$ ($\mu g/m^3$) |
|---|---|---|---|---|---|---|
| | | *Colbert-Lawrenceberg Line* | | | | |
| 1 | 11 | 2.2 | 20 | 152 | 1954 | 22 |
| 2 | 17 | 4.0 | 30 | 151 | 1954 | 20 |
| 3 | 24 | 6.8 | 26 | 172 | 1954 | 26 |
| 4 | 50 | 15.6 | 18 | 177 | 1954 | 17 |
| 5 | 85 | 26.2 | 30 | 212 | 1954 | 11 |
| | | *Colbert-Reynolds Line* | | | | |
| 6 | 5 | 1.3 | 178 | 132 | 1954 | 17 |
| 7 | 10 | 3.2 | 178 | 131 | 1954 | 14 |
| 8 | 20 | 6.0 | 145 | 208 | 1954 | 10 |
| 9 | 37 | 11.9 | 125 | 130 | 1954 | 7 |
| 10 | 77 | 24.5 | 110 | 171 | 1954 | 3 |
| | | *Colbert-Tupelo Line* | | | | |
| 11 | 9 | 2.4 | 260 | 146 | 1954 | 20 |
| 12 | 15 | 4.3 | 250 | 148 | 1954 | 17 |
| 13 | 29 | 7.2 | 242 | 286 | 1954 | 23 |
| 14 | 40 | 13.5 | 244 | 251 | 1954 | 15 |
| 15 | 80 | 27.4 | 231 | 217 | 1954 | 9 |
| | | *Colbert-Pickwick Line* | | | | |
| 16 | 76 | 15.6 | 18 | 177 | 1939 | 14 |
| 17 | 96 | 21.2 | 355 | 195 | 1939 | 27 |
| 18 | 114 | 24.5 | 350 | 249 | 1939 | 35 |
| | | *Wilson-Oakland-Colbert Line* | | | | |
| 19 | 53 | 14.6 | 55 | 168 | 1939 | 11 |

[a]For towers within 6-km radius $SO_2$ estimates were based on three year averages from nine monitoring sites. Other estimates were made using MULTIMAX model [14].

Average relative humidity: 70.5 %.

Average windspeed: at 10 m, 4.92 m/sec; at 100 m, 10.8 m/sec.

Elcometer Model 150 Minitector® with a resolution of 2.5 μm (0.1 mil). The measurements were not truly random because of the roughness of the surface and the lack of repeatability of measurements made on the same rough spot. To reduce the variability, three replicate measurements were taken at each point and as smooth an area as possible was chosen for measurement. These values on each point were averaged. Values were taken at nine points on each member. The values in Table 1.2 represent averages of the nine averages of three values. This procedure reduced the standard deviation on each mean, but also increased the probability that the mean differs significantly from the true mean.

The overall best estimate of the standard deviation of measurements about each of the means in Table 1.2 is ±12.7 μm. This value is much lower than normally is observed for hot dip galvanizing, possibly as a result of the measuring

TABLE 1.2 AVERAGE GALVANIZING THICKNESSES ON MEMBERS OF TRANSMISSION LINE TOWERS

| Tower number | Height of highest point | Height Side | Galvanizing thickness (μm)[a] 1 m Right | 1 m Left | 3 m Right | 3 m Left | 9 m Right | 9 m Left | Highest point Right | Highest point Left |
|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | *Leg* | | | | | |
| 1 | 24.4 | | 124.5 | 122.4 | 113.3 | 98.6 | 149.4 | 144.3 | 268.7 | 128.5 |
| 2 | 24.4 | | 170.2 | 171.7 | 207.8 | 206.2 | 148.3 | 170.7 | 133.1 | 126.0 |
| 3 | 25.6 | | 166.1 | 169.2 | 156.5 | 173.7 | 208.8 | 119.9 | 141.2 | 99.1 |
| 4 | 17.1 | | 144.8 | 125.5 | 166.6 | 139.7 | 101.1 | 150.9 | 305.3 | 152.4 |
| 5 | 17.1 | | 172.7 | 138.7 | 204.7 | 137.7 | 162.6 | 143.8 | 93.5 | 81.8 |
| 6 | 24.4 | | 154.4 | 149.9 | 145.8 | 130.0 | 132.1 | 106.2 | 100.1 | 122.4 |
| 7 | 17.1 | | 144.3 | 132.6 | 180.3 | 130.0 | 159.5 | 120.9 | 82.8 | 125.0 |
| 8 | 18.3 | | 108.7 | 192.0 | 118.9 | 190.0 | 164.6 | 179.8 | 198.6 | 115.3 |
| 9 | 22.0 | | 170.7 | 143.3 | 161.5 | 229.6 | 130.6 | 240.8 | 145.8 | 162.6 |
| 10 | 23.2 | | 128.5 | 131.6 | 219.5 | 267.2 | 242.3 | 122.9 | 100.1 | 112.8 |
| 11 | 15.9 | | 137.7 | 158.5 | 100.6 | 143.3 | 142.2 | 125.0 | 145.3 | 136.1 |
| 12 | 22.0 | | 143.3 | 130.6 | 106.7 | 103.1 | 138.7 | 172.2 | 89.9 | 90.9 |
| 13 | 18.3 | | 128.5 | 86.9 | 81.8 | 176.8 | 130.0 | 100.6 | 121.9 | 95.5 |
| 14 | 17.1 | | 139.2 | 143.3 | 135.6 | 149.9 | 212.9 | 153.4 | 131.6 | 140.7 |
| 15 | 22.0 | | 139.7 | 118.4 | 114.3 | 122.4 | 106.7 | 109.2 | 108.2 | 99.6 |
| 16 | 23.2 | | 137.7 | 126.0 | 125.0 | 121.4 | 131.6 | 125.0 | 124.0 | 125.0 |
| 17 | 25.6 | | 85.9 | 105.2 | 91.9 | 117.3 | 108.2 | 119.9 | 118.4 | 114.8 |
| 18 | 23.2 | | 100.1 | 102.1 | 102.1 | 84.3 | 101.6 | 107.7 | 118.4 | 122.4 |
| 19 | 22.0 | | 119.4 | 110.7 | 97.5 | 93.0 | 134.1 | 147.3 | 80.8 | 125.5 |
| | | | | | *Cross Member* | | | | | |
| 1 | 24.4 | | 134.6 | 124.0 | 92.9 | 110.0 | 126.5 | 195.6 | 61.0 | 124.0 |
| 2 | 24.4 | | 117.6 | 232.4 | 144.8 | 171.5 | 97.3 | 165.9 | 125.2 | 135.9 |
| 3 | 25.6 | | 129.5 | 104.1 | 111.8 | 127.0 | 70.6 | 100.3 | 111.8 | 94.7 |
| 4 | 17.1 | | 127.0 | 109.2 | 130.3 | 115.1 | 130.3 | 198.9 | 151.9 | 159.5 |
| 5 | 17.1 | | 179.8 | 141.7 | 181.6 | 157.0 | 122.7 | 146.8 | 74.9 | 77.5 |
| 6 | 24.4 | | 119.4 | 102.9 | 102.9 | 92.7 | 74.4 | 125.7 | 102.9 | 102.4 |
| 7 | 17.1 | | 113.8 | 123.2 | 127.8 | 130.3 | 175.3 | 73.7 | 93.5 | 125.2 |
| 8 | 18.3 | | 194.3 | 102.9 | 92.2 | 117.6 | 207.0 | 78.2 | 101.6 | 116.8 |
| 9 | 22.0 | | 173.5 | 148.6 | 106.7 | 107.4 | 168.4 | 128.3 | 128.3 | 107.4 |
| 10 | 23.2 | | 87.1 | 116.3 | 123.2 | 92.2 | 255.0 | 140.5 | 74.9 | 108.7 |
| 11 | 15.9 | | 156.2 | 144.3 | 140.5 | 129.0 | 134.6 | 115.1 | 132.8 | 127.0 |
| 12 | 22.0 | | 130.8 | 130.3 | 88.4 | 113.0 | 120.1 | 120.7 | 85.1 | 104.9 |
| 13 | 18.3 | | 116.8 | 76.2 | 113.0 | 120.1 | 86.4 | 85.1 | 121.4 | 102.4 |
| 14 | 17.1 | | 127.8 | 125.7 | 119.4 | 135.9 | 160.8 | 102.9 | 119.4 | 144.3 |
| 15 | 22.0 | | 89.7 | 124.0 | 98.6 | 118.1 | 139.7 | 136.7 | 139.7 | 107.4 |
| 16 | 23.2 | | 106.7 | 101.6 | 115.1 | 127.0 | 104.1 | 125.7 | 142.2 | 134.6 |
| 17 | 25.6 | | 96.0 | 105.4 | 131.6 | 114.3 | 131.6 | 120.7 | 63.5 | 65.3 |
| 18 | 23.2 | | 118.9 | 89.7 | 113.8 | 114.3 | 104.9 | 109.2 | 116.8 | 123.2 |
| 19 | 22.0 | | 93.5 | 85.9 | 102.4 | 108.0 | 80.8 | 141.7 | 113.8 | 130.3 |

[a]Underlined values were determined to be extremes possibly caused by measurement selection process.

procedure. The standard deviation is expected to be around 20% of the mean of 129.5 μm or ±25.9 μm.

Table 1.3 gives the results of analysis of variance of the data in Table 1.2. The variance associated with the quadruple interaction is used as error variance in the *F*-test for significance. Expressed as a standard deviation, the error is ±26.4 μm, which is very close to the expected value. It is most likely the best estimate of the true standard deviation and will be used in subsequent analysis. The most significant difference in thickness is associated with the type of structural member. Differences between towers and height on each tower were also significant. Neither the side of the towers nor any of the interactions were significant. Thus, the data are amenable to a normalizing procedure using average differences.

The means were normalized for the effects of tower and type of structural member and checked for outlying observations using ASTM recommended practice E 178 [16].

$$T^1 = \frac{(x - \bar{x})}{S_v} \qquad (2)$$

where $T^1 = 2.97$ for $n = 8$ and 54 degrees of freedom at the 1% level

$S_v = 26.4$ μm

$x$ = normalized mean.

Using this technique, 8 of the 304 values in Table 1.2 (underlined) are indicated to be outlying observations. All were on the high side, exceeding 212 μm. This fact indicates that the measured values are not normally distributed. The selection process used in getting the measurements could have biased the results by favoring areas with upper extremes of initial galvanizing thickness. The specified minimum galvanizing thickness was 2 oz/ft$^2$ or approximately 86.4 μm. Because of the expected variability in thickness, galvanizers apply much thicker coatings in order to meet this specification. With a standard deviation of 26.4 μm, the mean thickness must be 140 μm to have less than a 1 in 40 chance of not meeting the specification. With a normal distribution there would also be a similar chance that the thickness exceeds 193 μm. In Table 1.2 1 out of 16 means exceed that value even after 25 or more years of exposure. The indicated outlyers which contribute to a nonnormal distribution were excluded from further analysis based on normal statistics. This reduces a possible bias in the resulting analysis.

The mean thickness for tower leg measurements is 133.1 μm compared with a mean thickness of cross members of 119.4 μm. The 13.7-μm difference is probably an initial thickness difference because corrosion rates are expected to be the same.

TABLE 1.3 ANALYSIS OF VARIANCE OF GALVANIZING THICKNESS DATA

| Variable | Sum of squares | Degrees of freedom | Mean square | $F^a$ |
|---|---|---|---|---|
| Type (T) | 21,860.42 | 1 | 21,860.62 | 31.42** |
| Tower (L) | 77,046.88 | 18 | 4,280.38 | 6.15* |
| Height (H) | 10,463.48 | 3 | 3,487.83 | 5.01* |
| Side (S) | 429.88 | 1 | 429.88 | 0.62 |
| T × L | 17,008.92 | 18 | 944.94 | 1.36 |
| T × H | 1,393.47 | 3 | 464.49 | 0.67 |
| T × S | 386.32 | 1 | 386.32 | 0.55 |
| L × H | 81,384.27 | 54 | 1,507.12 | 2.17 |
| L × S | 10,646.19 | 18 | 591.45 | 0.85 |
| H × S | 2,008.62 | 3 | 669.54 | 0.96 |
| T × L × H | 49,841.01 | 54 | 922.98 | 1.33 |
| T × L × S | 21,807.43 | 18 | 1,211.52 | 1.74 |
| T × H × S | 2,734.93 | 3 | 911.64 | 1.31 |
| L × H × S | 56,157.99 | 54 | 1,039.96 | 1.49 |
| T × L × H × S | 37,587.95 | 54 | 696.07 | |

[a]Quadruple interaction used as denominator in *F*-test.

**Significant at 0.9995 probability level.

*Significant at 0.95 probability level.

The mean thicknesses as a function of height are 128.5, 129.5, 130.8, and 115.7 μm, respectively, for 1 m, 3 m, 9 m, and the highest point. The significantly different value is from the highest point. Corrosion is expected to be greater at the top of towers. Not only is the top more likely to be subjected to plume fumigations, but also, the increase in wind velocity from the ground causes higher pollution deposition velocities at the top [9].

The rates of corrosion on each tower vary with the environment to which the tower is exposed. Pollution levels and exposure time are variables causing differences in thicknesses between towers.

A multiple regression analysis was performed on the data using dummy variables for height and members type. Exposure time and $SO_2$ dose were also independent variables. Dose was taken as the ground level concentration times 25 years. The towers exposed for 40 years were constructed for a hydroelectric plant, thus, they were assumed to be exposed in a pollution-free environment for 15 years. The dummy variables were "1" for legs with "0" for cross members, and "1" for 1, 3 and 9 m with "0" for the highest points. The results are given in Table 1.4.

Although the coefficient for $SO_2$ dose is only marginally significant, both the sign and the magnitude are consistent with the results of previous studies [9]. The height variable was analyzed as if there were a difference in the initial thickness. The actual cause is more likely a higher average corrosion rate at the highest points. The corrosion rate is consistent with the value from Eq. 1.

Both wind velocity and time-of-wetness affect corrosion rate of galvanizing [9]. From wind velocity data (Table 1.1) the averages at lower heights and at the highest points are estimated at 2.7 m/sec and 6.75 m/sec, respectively. The ratio of these two values and an analogy between mass and momentum transfer [9] can be used to estimate $SO_2$ levels at the highest points. The concentration at the highest points should be approximately 2.5 times higher than at the lower heights (assumes steady state flux of pollutants to the ground).

Deposition velocities vary with windspeed. The respective calculated deposition velocities at the lower and higher heights are 0.64 and 1.27 cm/sec. The corrosion rate associated with pollution is proportional to the flux of pollutant to the corroding surface. Concentration times deposition velocity is a flux term. Thus, a coefficient for $SO_2$ dose at ground level should be nearly five times higher on members at the highest point. At an average $SO_2$ ground level concentration of 16.8 $\mu g/m^3$ the 9.4-μm difference between the lower and higher heights represents a 3.3 times higher coefficient. Other pollutants such as $NO_2$ can contribute to this difference [17].

The fraction of time the galvanizing surface is wet can be estimated from the average relative humidity of 70.6% from Table 1.1 and an empirical relationship developed from relative humidity distribution data [17]:

$$f = e^{[-3.35((100 - \text{RH avg})/\text{RH avg})]} \qquad (3)$$

where $f$ is the fraction of time when wet and RH avg is the average relative humidity.

The towers are expected to be wet approximately 25% of the exposure time. Thus, a zinc corrosion rate relationship when wet is:

$$C_{r_w} = 3.9 + 0.0383\ SO_2 \qquad (4)$$

This relationship is consistent with the results of previous studies [9]. At a deposition velocity of 1 cm/sec a coefficient of 0.045 represents a stoichiometric reaction with $SO_2$. Conversely the coefficient of 0.0383 suggests a deposition velocity of 0.85 cm/sec corresponding to an average wind velocity of 3.9 m/sec.

The data in Table 1.2 and the results in Table 1.4 can be used to estimate when maintenance or

TABLE 1.4 MULTIPLE REGRESSION ANALYSIS OF THICKNESS DATA

| Variable | Coefficient | Standard deviation | Partial $F$ | Probability of significance |
|---|---|---|---|---|
| Mean initial thickness for cross member | 144.4 μm | ±8.0 | 325.2 | >0.9995 |
| Member type (leg) | 13.4 μm | ±3.1 | 18.6 | >0.9995 |
| Time | −0.975 μm/yr | ±0.265 | 13.5 | >0.9995 |
| Height (1 m, 3 m, 9 m) | 9.4 μm | ±3.6 | 6.9 | >0.99 |
| $SO_2$ Dose | −0.00957 (μm/yr)(μg/m$^3$) | ±0.00872 | 1.2 | 0.73 |

replacement of these towers will have to be done. Spot painting can be performed when discoloration begins to show in the zinc-steel alloy portion of the galvanizing (approximately 38 μm). When 5% rust is present, painting the full structure may be needed. If the appearance of rust is acceptable, tower replacement could be delayed until 95% of the surface is rusted. Discoloration or rust will begin at the minimum thickness points or approximately two standard deviations below the mean on the cross members near the tops of the towers. Conversely two standard deviations above the mean on those same members will have to be corroded before 95% rust will have occurred. Considering the 3.3 times higher coefficient at the highest points, the minimum thickness as a function of time on the cross members is:

$$T_m = 91.6 - 0.975t - 0.0313\ SO_2\ t_e \quad (5)$$

where $T_m$ = minimum thickness, μm
$SO_2$ = ground level concentration, μg/m³
$t$ = years since installation
$t_e$ = years of $SO_2$ exposure

Add 106.5 for maximum thickness.

Based on this relationship the year can be estimated in which various types of maintenance for particular environmental conditions will be required. The results for these 19 towers are listed in Table 1.5.

It should be noted that other sources of pollution several miles to the west and to the east may have contributed to the overall corrosion of these towers and may be reflected in the time coefficient. The variation as a function of $SO_2$ in the area of these towers is most likely associated with the steam plant.

The three alternative approaches are estimated to be built upon annualized bases: (1) spot painting–most costly, (2) full painting–intermediate cost, and (3) replacement–least costly. The difference in time until initial maintenance occurs, and the maintenance frequency, are the main factors contributing to this relationship. These factors more than counteract the differences in cost per maintenance cycle.

Although waiting until most affected members are 95% rusted, and replacing towers, is the most economical approach, it is not likely to be aesthetically acceptable. Full structure painting meets aesthetic requirements and, in the long run, is likely to be more economical than spot painting. Spot painting must begin much sooner than full painting and must be done more often.

The cost of full structure painting can be annualized using the $SO_2$ damage function as a basis.

TABLE 1.5 YEAR IN WHICH FIRST MAINTENANCE IS EXPECTED

| Tower number | Existing environment | | | If $SO_2$ level had been maintained at 10% of existing level |
|---|---|---|---|---|
| | Spot painting | Painting | Replacement | Painting |
| 1 | 1986 | 2009 | 2073 | 2042 |
| 2 | 1987 | 2011 | 2077 | 2042 |
| 3 | 1984 | 2005 | 2064 | 2041 |
| 4 | 1990 | 2015 | 2085 | 2043 |
| 5 | 1995 | 2023 | 2103 | 2045 |
| 6 | 1990 | 2015 | 2085 | 2043 |
| 7 | 1992 | 2019 | 2094 | 2044 |
| 8 | 1996 | 2025 | 2107 | 2045 |
| 9 | 1999 | 2031 | 2119 | 2046 |
| 10 | 2004 | 2040 | 2138 | 2047 |
| 11 | 1987 | 2011 | 2077 | 2042 |
| 12 | 1990 | 2015 | 2085 | 2043 |
| 13 | 1986 | 2008 | 2070 | 2041 |
| 14 | 1991 | 2017 | 2091 | 2044 |
| 15 | 1997 | 2027 | 2111 | 2045 |
| 16 | 1982 | 2008 | 2083 | 2030 |
| 17 | 1975 | 1996 | 2054 | 2027 |
| 18 | 1973 | 1991 | 2042 | 2025 |
| 19 | 1984 | 2012 | 2092 | 2030 |

$$t = \frac{T_m}{(\alpha + \beta\, SO_2)\, f} \qquad (6)$$

where $t$ = years until maintenance occurs
$T_m$ = minimum thickness (mean - less two standard deviations)
$\alpha$ = time-of-wetness coefficient
$\beta$ = $SO_2$ coefficient
$f = e^{[-3.35((100 - RH\ avg)/RH\ avg)]}$
RH = average relative humidity

The costs are estimated as the loss of capital with rate of return from the time maintenance occurs until the time maintenance would have occurred if the $SO_2$ level were reduced by 90%. These costs are then annualized over the total time with $SO_2$ reduced by 90% and using the same rate of return. The relationship is

$$\text{annualized cost} = \frac{RQe^{Rtm}}{(e^{Rtm} - 1)} \sum_i \frac{1}{e^{Rti}} \qquad (7)$$

where $R$ = rate of return
$Q$ = cost of each maintenance cycle
$t_m$ = time with $SO_2$ level reduced by 90%
$t_i$ = time at which maintenance occurs

The annualized cost will be directly proportional to the cost per maintenance cycle. The effects of changes in other variables and coefficients is more difficult to calculate and visualize.

Figure 1.1 shows how changes affect the $SO_2$-maintenance cost damage function at a painting cycle cost of $1,000/tower. The annualized cost is a combination continuous and step function of $SO_2$ level. However, considering the possible variability in coefficients and other variables a simple direct proportion appears to be consistent with the functional shape of the relationships in Figure 1.1. A coefficient of ($0.65 ± 0.25)/tower-year-$\mu g/m^3$ can be used to estimate the annualized additional maintenance cost as a function of $SO_2$ level.

At an average of 17 $\mu g/m^3$ of $SO_2$ the average annualized extra maintenance cost on the towers associated with the Colbert Steam Plant is expected to be $11.05 ± 4.25/tower. In 1964, when TVA reported having 25,000 towers in service, the Colbert Steam Plant represented about

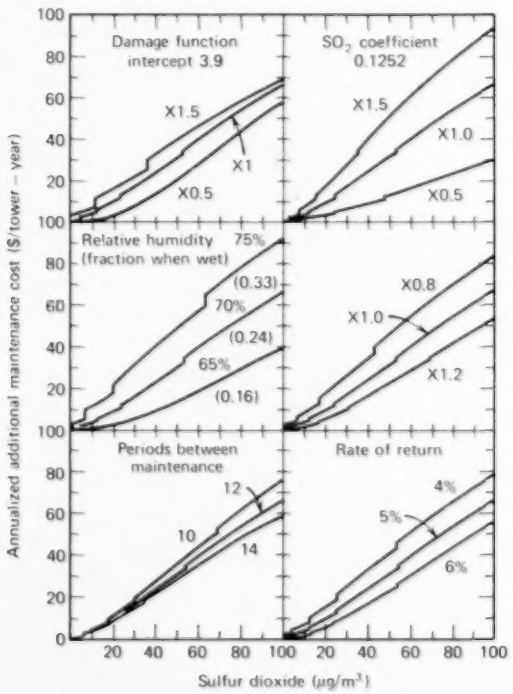


**Figure 1.1.** Effect of coefficient changes on $SO_2$-maintenance cost damage function at a painting cycle cost of $1,000/tower.

10% of TVA's total electric generating capacity. Assuming the plant generates 10 billion kWh/yr and its emissions affect 2,500 towers, the cost equals 0.0028 mills/kWh ± 0.0011 mills/kWh.

An average of 17 $\mu g/m^3$ of $SO_2$ may be considered a clean environment. Most sites in the northeast and north central states exceed an annual average of 30 $\mu g/m^3$. These levels are expected to increase as more coal is used to produce electricity. If levels were allowed to reach the primary ambient air quality standard of 80 $\mu g/m^3$, the annualized extra maintenance cost would be expected to be 0.0132 mills/kWh ± 0.0052.

Actual costs are not annualized, but will be the result of the long accumulated damage. In years when most existing towers have to be painted, the cost/kWh could be from 20 to 40 times higher.

The galvanizing thickness on transmission line towers is greater than is normally applied to pole line hardware, chain-link fencing, and roofing and siding materials. Thus, the frequency of maintenance and replacement of these other structures will be greater. Such structures owned by utilities will add to the extra maintenance cost. Thus, at the primary ambient air quality standard, the internalized cost of pollution could be as high as 0.04 mills/kWh. This appears to be a reasonable estimate when compared with costs to maintenance of structures of 0.33 mills/kWh and 0.08 mills/kWh reported for two steam plants by Commonwealth Edison [11]. It represents only a small fraction of the presently estimated 5.5 mills/kWh ± 2.4 mills/kWh for flue-gas-desulfurization control [18]. The reason for emission control regulations, however, is because the costs are externalized through the distribution of poilution rather than internalized.

## GALVANIZED ROOFING, SIDING, AND GUTTERING

With the possible exception of guttering, most of these materials are used in industrial and commercial buildings. Farm buildings represent the greatest direct use by consumers.

Maintenance, replacement, and substitution are involved in considering the economic cost of pollution damage to these galvanized products. When bare galvanized sheet metal begins to rust it can be painted to extend its life. In some cases it may be cheaper to replace than paint. In severe environments substituting a more durable but more expensive material may be the most economical approach. Two common substitute materials are aluminum and factory coil-coated galvanized steel. Sales of both precoated steel and aluminum have experienced growth that exceeds that of roofing, siding, guttering, and prefabricated buildings as a total.

The maximum amount of roofing, siding, and guttering in the United States can be estimated from production figures given in 1972 and earlier census of manufactures [19]. Table 1.6 gives these production figures for steel and aluminum roofing, siding, and guttering.

The rate of production of steel fits the equation

$$A_s = e^{[0.065(yr - 1896)]} \pm 10.2\% \qquad (8)$$

and aluminum fits

$$A_a = e^{[0.072(yr - 1913)]} \pm 8.3\% \qquad (9)$$

Integrating these equations with time gives the total amount produced prior to a specific year. The results are given in Table 1.7.

Not all of the roofing, siding, and guttering that has been produced remains in service. Corro-

TABLE 1.6 ANNUAL U.S. PRODUCTION OF ROOFING, SIDING, AND GUTTERING

| Year | Steel Surface area[a] $(km)^2$ | Steel shipment value ($ million) | Steel Unit cost ($/m^2$) | Aluminum Surface area[a] $(km)^2$ | Aluminum shipment value ($ million) | Aluminum Unit cost ($/m^2$) |
|---|---|---|---|---|---|---|
| 1947 | 31.0 | 58.6 | 1.89 | 12.2 | 284.0 | 2.32 |
| 1954 | 40.9 | 79.8 | 1.95 | 17.8 | 48.3 | 2.71 |
| 1958 | 53.0 | 103.6 | 1.95 | 24.6 | 75.4 | 3.07 |
| 1963 | 89.7 | 165.4 | 1.84 | 41.4 | 121.4 | 2.93 |
| 1967 | 108.4 | 207.4 | 1.91 | 50.6 | 139.3 | 2.75 |
| 1972 | 141.2 | 347.7 | 2.46 | 68.2 | 152.5 | 2.24 |

[a]Surface area calculated assuming $1.32 \times 18^{-4}$ $km^2$/ton for steel and $3.26 \times 10^{-4}$ $km^2$/ton for aluminum.

TABLE 1.7 ESTIMATED TOTAL U.S. PRODUCTION OF ROOFING, SIDING, AND GUTTERING PRIOR TO A GIVEN YEAR

| | Surface area ($km^2$) | | | Per capita surface area ($m^2$/person) | | |
|---|---|---|---|---|---|---|
| Year | Steel | Aluminum | Both | Steel | Aluminum | Both |
| 1920 | 57.8 | 9.1 | 66.9 | 0.67 | 0.10 | 0.77 |
| 1930 | 124.9 | 33.3 | 158.2 | 1.22 | 0.33 | 1.55 |
| 1940 | 253.3 | 83.1 | 336.4 | 2.11 | 0.69 | 2.80 |
| 1950 | 499.2 | 185.5 | 684.7 | 3.57 | 1.33 | 4.90 |
| 1960 | 970.3 | 395.7 | 1366.0 | 5.72 | 2.33 | 8.05 |
| 1970 | 1872.8 | 827.5 | 2700.3 | 9.68 | 4.28 | 13.96 |

sion is probably the major reason for removals from service. Knowing input minus output equals accumulation, with the above data and estimates of amounts in existence at particular times, the amount lost can be estimated. Conversely with damage functions and estimates of pollution levels the amounts lost can be estimated.

Through a contract for EPA, Geomet, Inc., did a study of the distribution of materials in Baltimore, Maryland, and St. Louis, Missouri [20]. Sanborn Atlases developed by the Sanborn Map Company of Pelham, New York, were used as the primary source of data with respect to amounts and types of surfaces. Visual surveys were used as a check on the estimated percentages of different types of materials. These data were correlated with census tract data for 62 tracts in Baltimore and 48 tracts in St. Louis. The exposed materials were disagregated into roof and wall, and residential, commercial, and industrial. The amounts of 11 types of wall material and 8 types of roof material were estimated for each class. Sheet metal was one of the types of materials.

The single most important variable from the census data that correlated with surface area density was population density. Thus, per capita amounts of surface area is a useful parameter in estimating the distribution of various materials. In Baltimore the materials distribution was estimated from 1971–72 data, whereas the population data were for 1970.

In St. Louis the Sanborn Atlas data used to estimate the amounts of materials were from the mid-1950s, thus, the 1950 census data were used to get the populations of tracts.

The overall results based on the collected data are given in Tables 1.8 and 1.9.

These figures indicate that the existing per capita amounts of metal roofing and siding were 0.39 $m^2$/person in St. Louis in 1950 and 2.27 $m^2$/person in Baltimore in 1970. These results are based on center city data, whereas the data in Table 1.7 are for the entire United States. Both Baltimore and St. Louis were well developed at the time the data were collected and the materials are mostly on older structures. Thus, the ages of structures are needed before comparisons of the two types of data should be made. Table 1.10 gives the fraction of housing constructed in different periods

Multiplying the fractions in Table 1.10 by the comparable amounts accumulated in each period from Table 1.7 and adding gives estimates of the inplace amounts without losses. The results are 1.00 $m^2$/person for St. Louis and 2.93 $m^2$/person for Baltimore. These values include guttering, whereas the inplace estimates from the Geomet

TABLE 1.8 PER CAPITA AMOUNTS OF WALL AND ROOF SURFACES IN BALTIMORE AND ST. LOUIS–$m^2$/PERSON

| | Baltimore | | St. Louis | |
|---|---|---|---|---|
| Use | Wall | Roof | Wall | Roof |
| Residential | 28.4 | 15.8 | 37.5 | 17.9 |
| Commercial | 11.9 | 10.0 | 15.6 | 9.4 |
| Industrial | 12.1 | 18.8 | 8.8 | 9.8 |

TABLE 1.9 PERCENTAGES OF CLASSES OF SURFACES THAT ARE SHEET METAL IN BALTIMORE AND ST. LOUIS

| | Baltimore | | St. Louis | |
|---|---|---|---|---|
| Use | Wall | Roof | Wall | Roof |
| Residential | 0.06 | 0.00 | 0.07 | 0.00 |
| Commercial | 3.01 | 1.23 | 0.21 | 0.00 |
| Industrial | 8.82 | 3.77 | 3.71 | 0.08 |

TABLE 1.10 FRACTION OF HOUSING IN BALTIMORE AND ST. LOUIS CONSTRUCTED IN GIVEN PERIODS

| Period | Baltimore | St. Louis |
|---|---|---|
| Before 1920 | | 0.7792 |
| 1920–1929 | | 0.1461 |
| 1930–1939 | | 0.0846 |
| Before 1940 | 0.6435 | |
| 1940–1949 | 0.1286 | 0.0880 |
| 1950–1959 | 0.1240 | |
| 1960–1969 | 0.0878 | |

data do not. Guttering amounts to about 11% of production. Including guttering, the inplace amounts are 0.44 $m^2$/person for St. Louis and 2.55 $m^2$/person for Baltimore.

The differences between input and existing amounts represent losses of 0.56 $m^2$/person in St. Louis and 0.38 $m^2$/person in Baltimore. Assuming no loss of the aluminum these values represent a loss of the galvanized steel installed in St. Louis prior to 1923 and in Baltimore prior to 1934. The respective average lifetimes are estimated to have been 27 and 36 years.

With an $SO_2$ damage function for galvanized steel based on data obtained in St. Louis [9] and assuming a thickness of galvanizing and average relative humidity for each city the amount of $SO_2$ required to produce these lifetimes can be estimated. The damage function can be expressed as:

$$t = \frac{25\ \mu m}{(2.4 + 0.02\ SO_2) f} \tag{10}$$

where $t$ = lifetime in years

$f$ = fraction of time when wet

$= e^{[-3.35((100 - \text{RH avg})/\text{RH avg})]}$

RH avg = average relative humidity; 69 for St. Louis, 65 for Baltimore

The results are 88 $\mu g/m^3$ for St. Louis and 90 $\mu g/m^3$ for Baltimore. The respective averages from National Air Surveillance Network data from the 1960's are 116 $\mu g/m^3$ and 72 $\mu g/m^3$. Therefore, inplace amounts are consistent with expected lifetimes and production amounts. This consistency suggests that a model can be developed to estimate the present distribution of various types of metal surfaces, for example, both bare- and coil-coated galvanized steel and aluminum.

The coil-coated products and the bare aluminum products are not affected appreciably by corrosion including the corrosion caused by sulfur dioxide. Thus, most of these products should still be in service. From annual coil-coating production figures from 1962 to 1974 [21] and assuming 50% of the steel and 30% of the aluminum is used for roofing, siding, and guttering, equations for annual production are

$$A_{cs} = e^{[0.128(t - 1936)]} \pm 18.3\% \tag{11}$$

for coil-coated steel, and

$$A_{c_a} = e^{[0.121(t - 1938)]} \pm 14.6\% \tag{12}$$

for coil-coated aluminum

where $A$ = surface area ($km^2$)

$t$ = year

The average growth rate of production of these products is nearly twice as fast as the growth rate for the total production of roofing, siding, and guttering. Extrapolating Eq. 10 and 11 into the future beyond the range of data gives values that exceed totals from extrapolating Eq. 7 and 8. Because this behavior is not possible and markets for products are not infinite, a constant growth rate equation is not a useful predictor over a long range.

When a product is new and has a potentially large market, production usually follows a constant growth rate curve. During an intermediate stage the growth is constant with time. Then, the market becomes saturated; the growth rate declines. Finally, as other products are substituted, the market declines. The first three stages of production can be modeled with a Gompertz curve:

$$\ln Y = \ln K + b^X \ln a \tag{13}$$

where $Y$ = annual production

$X$ = a time factor

$K, b, a$ = constants.

Coefficients from curve-fitting available data are given in Table 1.11. The curve for bare galvanized steel was obtained on values calculated as the difference between total production and coil-coated steel production. Similar data for bare aluminum showed a decline in production which does not fit a Gompertz curve. The production rate of this product was assumed to be constant at 9.3 $km^2$/yr after 1967. Prior to that year the production of bare aluminum can be estimated from the difference between the total production from Eq. 8 and the Gompertz curve for the coil-coated aluminum.

Figure 1.2 shows the projected production of the different types of roofing, siding, and gutter-

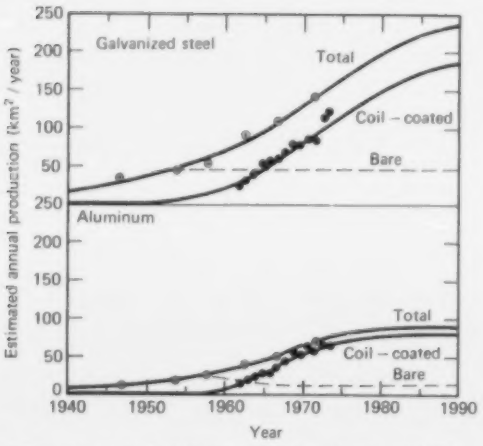


**Figure 1.2.** Projected U.S. annual production of different types of roofing, siding, and guttering.

ing to 1990. The annual production of bare galvanized steel appears to remain relatively constant at 48.5 $km^2$/yr after 1955. Summation of the annual production figures prior to a given year gives the total production up to that time of each product. The results for 1970 and 1980 are given in Table 1.12.

Bare aluminum, and the two coil-coated products are relatively new when compared with bare galvanized steel, and are not affected appreciably by corrosion. Consequently, most of these products should still be in existence. By contrast much of the bare galvanized steel is lost because of corrosion. Some of the additional costs associated with the substitution of these more durable products can be attributed to the effects of air pollution. The coil-coated products also are aesthetically more attractive. Because bare aluminum is not affected by corrosion, the relative value of aesthetics is indicated by the production rates of bare and coil-coated aluminum. In 1980 only 11% of the aluminum was bare. Thus, 11% of the cost differential between bare steel and coil-coated steel may be attributed to corrosion avoidance rather than aesthetics. Most of the differential between bare aluminum and bare galvanized steel should be corrosion avoidance cost.

Table 1.13 gives the estimated costs for various products and maintenance.

Based on the estimated production of coil-coated galvanized steel and bare aluminum in 1980 and a population of 230 million people, the annual per capita cost of using substitute materials to avoid corrosion is only \$0.10/person. This is a cost of the perceived effects of pollution at any level and may be represented as the cost intercept at zero pollution, on a cost-pollution level curve.

Some of each year's production of roofing, siding, and guttering is used to replace losses of bare galvanized steel. In general, the amount increases each year, because, up until 1955 the annual production of bare galvanized steel increased with time. A model of any past year's

TABLE 1.11 GOMPERTZ ANNUAL PRODUCTION CURVE COEFFICIENTS FOR ROOFING, SIDING, AND GUTTERING[a]

| | Galvanized steel | | Aluminum |
|---|---|---|---|
| | Bare | Coil coated | Coil coated |
| $X$ | $(t - 1947)/5$ | $t - 1963$ | $t - 1963$ |
| $\ln K$ | 3.881 | 5.419 | 4.371 |
| $b$ | 0.347 | 0.916 | 0.817 |
| $\ln a$ | -0.566 | -1.915 | -1.558 |

[a] $t$ = year of production, production ($Y$) = $km^2$ of surface area.

TABLE 1.12 TOTAL PRODUCTION OF ROOFING, SIDING, AND GUTTERING FROM DIFFERENT MATERIALS

| | 1970 | | 1980 | |
|---|---|---|---|---|
| Type of material | Surface area ($km^2$) | Per capita surface area ($m^2$/person) | Surface area ($km^2$) | Per capita surface area ($m^2$/person) |
| Bare galvanized steel | 1411.0 | 7.29 | 1896.0 | 8.25 |
| Coil coated steel | 571.2 | 2.95 | 1753.1 | 7.63 |
| Bare aluminum | 523.8 | 2.71 | 616.8 | 2.68 |
| Coil coated aluminum | 317.0 | 1.64 | 1002.6 | 4.36 |
| Total | 2823.0 | 14.59 | 5268.5 | 22.92 |

TABLE 1.13 ESTIMATED AVERAGE COST FOR ROOFING, SIDING, AND GUTTERING IN 1980 AT THE CONSUMER LEVEL ($/m$^2$)

| Product | Base material | Coil coating | Installation | In place painting | |
|---|---|---|---|---|---|
| | | | | First rust | Considerable rust |
| Galvanized steel | 3.50 | 1.50 | 7.00 | 4.00 | 8.00 |
| Aluminum | 5.00 | 1.50 | 6.00 | | |

production that must be replaced prior to the end of the present year is

$$f = a\left(\frac{1}{t_p - t} + 1\right) e^{-b/(t_p - t)} \qquad (14)$$

where $f$ = fraction of production in year $t$
$t_p$ = present year
$a$ and $b$ = constants determined by assuming median and maximum lives

The maximum life will occur in a clean environment and, thus, is not dependent on pollution levels. The median life is a function of average pollution level. According to Eq. 6, assuming a maximum life of 70 years corresponds to a completely rusted surface at an average relative humidity of 68%, with the same relative humidity, the surface half rusted, a medium life of 35 years corresponds to a median average $SO_2$ level of 53 $\mu g/m^3$. At a medium life of 45 years the $SO_2$ level is 14 $\mu g/m^3$.

With the coefficients calculated, multiplying Eq. 14 by the annual production and summing to the present year gives an estimate of the total amount of bare galvanized steel that has gone out of service. The difference between the present year and the previous year is an estimate of the amount of the present year's production used for replacement. Table 1.14 gives the results assuming different median lives.

The assumed median lives correspond to a 10-fold difference in average pollution levels, yet the amount replaced in 1980 differs by less than 70% and the amount in existance by less than 24%. Thus, the estimates of amounts in existance and being replaced should be accurate within ±35%.

With cost estimates from Table 1.13 and an assumed median life of 35 years, the national per capita cost of replacing bare galvanized steel in 1980 is calculated to be $1.21/person. At 48 years the per capita replacement cost is $0.71/person. The difference is the average per capita cost of the effect of pollution on bare galvanized roofing, siding, and guttering in 1980. This calculates to be $0.50/person or $115 million for the nation.

The amount spent this year is for damage that has occurred in past years. The costs in future years depend on future pollution levels and the total amounts of bare galvanized roofing, siding, and guttering in existence.

In 1950 the per capita amount of all roofing, siding, and guttering in the center city of St. Louis was estimated to be 0.44 $m^2$/person. In 1970 in Baltimore the amount was 2.55 $m^2$/person. A constant growth rate extrapolation in 1980 gives an estimate of 6.14 $m^2$/person for center cities. This is considerably less than the national average of 20.84 $m^2$/person taken from Tables 1.12 and 1.14.

As shown in the previous analysis, the age of the structure affects the amount that was originally installed and center city structures are older than the national average. Thus, the per capita amounts in suburban and rural areas must be higher than average.

TABLE 1.14 ESTIMATES OF THE EFFECTS OF ASSUMING DIFFERENT MEDIUM LIVES OF BARE GALVANIZED STEEL ON AMOUNT IN SERVICE AND AMOUNT OF PRODUCTION USED FOR REPLACEMENT IN 1980

| Median life | | Total amount consumed ($km^2$) | Total amount in existance ($km^2$) | Replacement in 1980 ($km^2$) | Per capita in existance ($m^2$/person) | Amount replaced in 1980 ($m^2$/person) |
|---|---|---|---|---|---|---|
| Years | $SO_2$ Level ($\mu m/m^3$) | | | | | |
| 35 | 53 | 476.9 | 1419.1 | 26.4 | 6.17 | 0.115 |
| 45 | 14 | 282.7 | 1613.3 | 18.0 | 7.01 | 0.078 |
| 48 | 5.3 | 233.2 | 1752.8 | 15.5 | 7.62 | 0.061 |

The per capita distribution of bare galvanized steel between center cities and surburban and rural areas should vary even more than the totals for roofing, siding, and guttering. Center cities historically have experienced the highest average pollution levels, thus the likelihood of old bare galvanized steel still in existence in these areas is small. The perceived effects of pollution and the desire for a more aesthetic product would tend to cause the replacement of bare galvanized steel with coil-coated products.

The continued use of bare galvanized steel roofing, siding, and guttering is expected to be in farm and suburban light industrial buildings. Most are exposed to relatively clean environments similar to those to which transmission line towers are exposed.

Those individuals owning such structures probably represent less than 10% of the total population. At least a portion of the costs of replacement, however, will be passed on to the public in the form of higher prices for farm products and manufactured goods.

It is estimated that less than 10% of today's population live in center cities that would have experienced high average $SO_2$ levels in the past. The per capita amount of bare galvanized surface for these persons is estimated to be 0.05 $m^2$/person or 1.15 $km^2$ total. That leaves nearly all of the estimated 1419.1 $km^2$, from Table 1.14 existing in suburban and rural areas or center cities with comparable low levels of $SO_2$.

Thus, the per capita distribution of bare galvanized steel roofing, siding, and guttering in suburban and rural areas is expected to be at least 6 $m^2$/person and possibly as high as 8 $m^2$/person. The amounts in center cities is expected to be relatively small. With a figure of 7 $m^2$/person and the population distribution within an area, the distribution of bare galvanized roofing, siding, and guttering within that area can be estimated.

The damage function from Eq. 6 can be used to estimate times between replacement or maintenance as a function of $SO_2$ level and average relative humidity. The cost per cycle of maintenance can be taken from Table 1.13.

Coil-coated galvanized steel products will be relatively unaffected by $SO_2$ levels and have a lifetime of at least 70 years. Amortizing \$12/$m^2$ installation costs over 70 years at 5% gives an annualized cost of \$0.0187/$m^2$. That is, it would require an annual investment of \$0.0187/$m^2$ per year at a 5% return to accumulate \$12/$m^2$ in 70 years.

With annual substitution costs estimated at \$0.10/person and the 1980 costs for replacing past $SO_2$ damaged products the damage function that includes all of the annualized costs is

$$c_p = 0.60 + (0.015 \pm 0.005)\, SO_2 \pm 0.30 \quad (15)$$

where $c_p$ = annual per capita cost (\$/person)
$SO_2 = \mu g/m^3$

and ± are confidence limits on coefficients.

At an average existing $SO_2$ level of 30 $\mu g/m^3$ the total annual cost per person could range from \$0.60 to \$1.50 with a best estimate of \$1.05. At the primary ambient air quality standard, the best estimate is \$1.80. In years after 1980, the catch-up cost of \$0.50/person should not be included in calculating total cost because further damage is considered in the amortization function.

Each year a portion of that year's production increases the existing stock that will be affected. Because population also increases, however, the cost per person function should not change significantly.

Equation 15 can be applied on a regional or national scale. In 1980, at 30 $\mu g/m^3$ and a population of 230 million, the total cost from $SO_2$ damage of bare galvanized steel roofing, siding, and guttering is estimated to be \$242 million with \$115 million of that going to replace prior damaged products.

The frequency of replacing or painting bare galvanized steel will vary with the $SO_2$ level. A technique similar to that used for transmission line towers can be used to calculate service lives and painting frequencies. Assuming a new product has a mean galvanizing thickness of 25.4 $\mu m$ and varies ±40%, complete rust will occur after 35.6 $\mu m$ corrodes, considerable rust after 25.4 $\mu m$, and first rust after 18.1 $\mu m$. Using the data in Table 1.13 and assuming a relative humidity of 68% and $SO_2$ level of 10 $\mu g/m^3$, and a five year painting cycle, the annualized costs to replace, to paint after considerable rust, and to paint after first rust are \$0.0194/$m^2$, \$0.0817/$m^2$, and \$0.1485/$m^2$, respectively. From these figures, a choice to paint bare galvanized steel is not made for economic reasons. Even for aesthetic reasons it would be better to replace with coil-coated galvanized steel rather than paint.

The thickness of galvanizing on the existing bare products varies with age and environment to which it is exposed. The cost of reduced life of the amounts of each year's production still existing must be amortized over its remaining life expectancy at a 90% reduction in pollution level. A 5% return was assumed and galvanized costs were

calculated for $SO_2$ levels from 0 to 100 $\mu g/m^3$. The results can be closely approximated by a linear relationship. Considering the magnitude of the effects of various assumptions that have been made, analogous to the evaluations on the transmission line tower data, the best estimate of the $SO_2$ coefficient is \$0.0150 ± 0.0050/person/yr/$\mu g/m^3$.

The use of New York City is an example of an application on a regional scale. In 1970 the population of the surrounding suburbs was around 7.5 million. During the 1960s the average $SO_2$ levels were 390 $\mu g/m^3$ in the center city. If the average in the suburbs had been allowed to remain at one-half that level, the cost in 1980 for that region would have been \$26.4 million. At 30 $\mu g/m^3$ the cost is expected to be \$7.9 million. The difference is a savings that can be attributed to reduced pollution levels.

As another example, both Colbert and Lauderdale counties in Alabama are affected by the emissions from the Colbert steam plant. In 1975 the population of these two counties was 123,318 [22]. Assuming the plant emissions contribute an average of 10 $\mu g/m^3$ to the pollution over the area, the annual cost from $SO_2$ damage to bare galvanized steel roofing, siding, and guttering is estimated to be \$92.5 thousand with a range from \$49.3 thousand to \$135.6 thousand. In terms of plant power production these costs are 0.0093 mills/kWh with a range of 0.0049 mills/kWh to 0.0136 mills/kWh. This externalized cost from damage to a single type of galvanized steel product is more than three times the internalized costs associated with the $SO_2$ damage to transmission line towers.

## CONCLUSIONS

The cost of air pollution accelerated corrosion can be quantified within reasonable confidence limits. These costs can be related to particular levels of pollutants using observed damage functions and models for the distribution of exposed products.

Transmission line towers represent structures for which considerable extra maintenance can be expected within the next few years. This internalized cost will very likely be passed on to the utilities' customers in rate increases of from 0.0017 to 0.0174 mills/kWh if the costs are annualized. If the costs are allowed to accumulate until the actual maintenance occurs, the rate increases will have to be higher.

Bare galvanized steel roofing, siding, and guttering are products that are affected by $SO_2$ in the atmosphere. These products are not located in center cities because, (1) the products were not being produced extensively when center city structures were erected, and (2) the pollution levels in center cities made it more desirable to substitute more pollution resistant products. The products are distributed by population with greater densities in suburban areas.

The per capita cost associated with the premature loss of bare galvanized roofing, siding, and guttering is \$1.50 ± 0.50 per $\mu g/m^3$ of $SO_2$ plus \$0.10 for substitution costs and \$0.50 in 1980 for prior years of accumulated damage. When related to coal-fired utility power production, the costs can range from 0.0049 mills/kWh to 0.25 mills/kWh depending on the ambient level of $SO_2$ contributed by power plants.

The externalized costs associated with the $SO_2$ damage of bare galvanized steel roofing, siding, and guttering greatly exceeds the internalized costs associated with extra maintenance on transmission line towers. Other galvanized steel products such as chain link fencing, pole line hardware, and wire rope are also damaged by $SO_2$. Costs for these products can be estimated in a similar manner. Painted steel structures represent another product type that can be subjected to benefit analysis.

When the costs associated with the premature replacement or maintenance of all of these products are calculated and added as a function of $SO_2$ level, it is very likely that some level of control will create a benefit that equals or exceeds the present cost of control of 5.5 mills/kWh. With expected reduction in control costs, lower ambient levels of $SO_2$ may be justified strictly from economic benefits. The possibility of quantifying extra benefits to health and ecology will be welcomed by-products.

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## DISCUSSION

F. MANSFELD* (written discussion). Where did your equations on lifetime come from? The dimension in these equations did not seem to come out as time. Please explain!

F. H. HAYNIE (author's closure). Lifetime is the galvanizing thickness divided by the corrosion rate, which is a function of the $SO_2$ level and the fraction of time that the surface is wet. With the thickness in $\mu$m and the corrosion rate in $\mu$m/year, lifetime is in years.

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